BOREHOLE AND FORMATION ANALYSES TO SUPPORT COMPRESSED AIR ENERGY STORAGE DEVELOPMENT IN RESERVOIRS

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ABSTRACT

A 2-D borehole/formation model was developed for Compressed Air Energy Storage (CAES) applications to evaluate the performance of the system under various conditions including two-phase flow. The optimum formation radius, which is directly related to borehole spacing, was determined for given sets of formation parameters, borehole diameter, and CAES operating assumptions based on minimum and maximum formation pressure values. The effect of two formation parameters, permeability and porosity, on the operational parameters was assessed using this model.

INTRODUCTION

Compressed air energy storage (CAES) in reservoirs relies on air flow through boreholes between the above-ground power plant and the underground reservoir. The efficiency of the underground portion of the CAES system depends in part on the porosity and permeability of the formation and on the details of the borehole array. The economic feasibility of a CAES facility may hinge on accessible air volume and/or air mass flow rate. When sufficient air volume and mass flow rates are available, optimal design of the borehole array, including borehole diameter and spacing, will determine the efficiency of the system.

In this study, formation (porosity, permeability, degree of saturation) and borehole parameters (diameter, length, and spacing) were evaluated to determine appropriate ranges for successful CAES application. The flow in the boreholes can be used to determine a minimum number of boreholes of a given diameter to minimize pressure losses while maintaining adequate air flow. In the formation, the flow to these boreholes depends on the formation porosity, permeability, pressure, and degree of saturation (water or gas filled) as well as the borehole diameter and borehole layout. For example, if the boreholes are spaced too close to each other, the flow rate per borehole is less than optimal and the borehole layout is inefficient because fewer boreholes could be used. Similarly, if the boreholes are spaced too far apart, the number of boreholes for the CAES formation will be less than optimal, so the plant capacity will also be less than optimal.

Problem Idealization

In a reservoir CAES facility, air is injected and withdrawn from the underground formation through a number of boreholes. For this study emphasis was placed on understanding the processes that occur for a unit borehole (i.e., one of the boreholes in the array). An idealized plan view of a unit borehole is shown in Figure 1. Each circle represents the flow distance to the nearest adjacent boreholes.

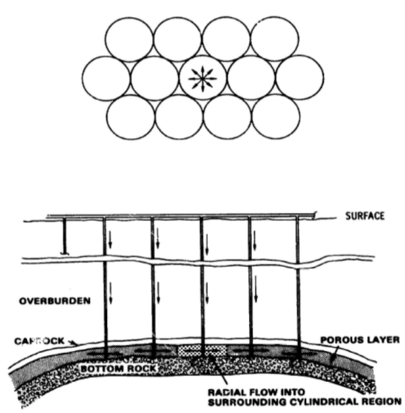

Figure 1. CAES borehole schematic plan and elevation view (Smith and Wiles, 1979).

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Simulations were performed using the TOUGH2 code (Pruess et al., 1999.) modified for CAES operations. TOUGH2 assumes Darcy (laminar) flow in the formulation. Turbulent flow near boreholes is often postulated in CAES operation (Smith and Wiles, 1979, pg. 330 and Katz and Lady, 1976, pg. 65 and elsewhere). However, turbulence is not a significant factor for CAES according to Pittsfield data (EPRI GS-6688, 1990, pg. 4-38), and turbulent flow in the formation was not included in the present simulations.

The simulations in this study modeled processes in a possible CAES formation, including the formation of the initial air bubble and the weekly cycling of air injection and withdrawal for a given formation radius. The resulting borehole/formation pressures were compared to pressure limits to evaluate the given formation radius.

Formation Details

The simulation model shown in Figure 2 consists of a single borehole in a formation with uniform properties (permeability, porosity, rock type); formation properties were varied in this study. The formation height is assumed to be 100 ft (30.5 m); gas flow is restricted to this height. The top boundary is impermeable cap rock. The outer radial boundaries are no-flow because other boreholes are assumed to surround this unit borehole. The bottom boundary is at hydrostatic pressure for the assumed depth. Water may flow into and out of this lower boundary to maintain hydrostatic pressure as well as any capillary fringe. Air may not flow across this boundary. The nominal completion position of the borehole is midway into the formation (50 ft; 15.2 m) to minimize water inflow during air withdrawal from water coning. The depth to the top of the formation is 2000 ft (610 m).

The radial dimension of the formation was varied to reflect CAES operating conditions and pressure limits. Based on this radial dimension, the initial air bubble is formed over a specified number of days. An equilibration time is specified before the weekly CAES injection/withdrawal cycles begin. The parameters are summarized in Table 1.

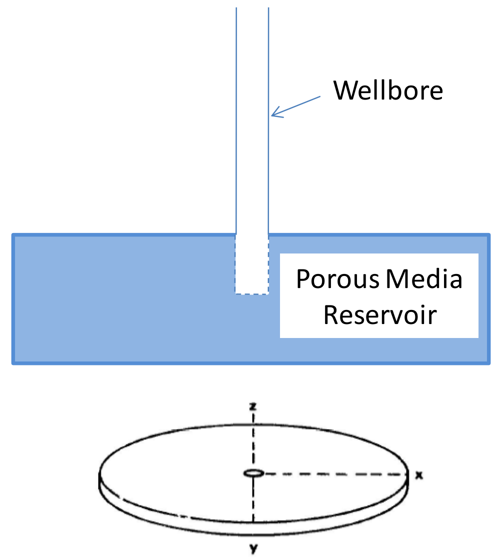

Figure 2. Borehole and formation geometry.

Table 1. Simulation parameters

Reservoir Depth (Top)	2000 ft (610 m)
Reservoir Height	100 ft (30.5 m)
Reservoir Pressure (Top)	880 psig (6.07 MPa)
Reservoir Temperature	25 °C
Borehole Diameters	7 inches (17.8 cm) 12 inches (30.5 cm) 20 inches (50.8 cm)
Porosity	Base Case: 0.2 Range: 0.1, 0.2, 0.3
Permeability	Base Case: 500 mD Range: 100, 500, 1000, 2000 mD
Capillary Pressure and Relative Permeability	Based on Zhou et al. (2010)
Air Bubble Parameters	
Development Time	60 days
Final Gas Saturation	0.5
Equilibration Time	40 days
Weekly CAES Cycle Parameters	
Injection/Withdrawal Rate	Variable
Injection Composition	Dry Air
Injection Temperature	25 °C
Weekly Cycled Air Mass	10%
Weekend Injection	40%
Borehole/Formation Pressure Limits	725 psia (5.0 MPa) 1220 psia (8.4 MPa)

The maximum borehole/formation pressure used in this study is 0.6 times lithostatic pressure, or 1220 psia (8.4 MPa). The minimum borehole/formation pressure is based on a turbine inlet pressure of about 650 psia (4.5 MPa) (Succar and Williams, 2008) and an approximate 75 psi (0.5 MPa) pressure drop from the formation to the surface based on gas-only flow up the borehole, or a minimum borehole/formation pressure of 725 psia (5.0 MPa).

The injection and withdrawal cycle used in these simulations is based on the scheme of Smith and Wiles (1979) as shown in Figure 3. Their weekly cycle consists of alternating 10-hour withdrawal and injection cycles, with 2-hour transition periods during the week and an additional injection on the weekend. The injection and withdrawal rates are based on a user-specified fraction cycled and fraction of mass injected during the weekend. The original cycle proposed by Smith and Wiles based the injection and withdrawal rates on the maximum mass in the air bubble. The present implementation modifies this scheme slightly; the injection and withdrawal rates are based on the initial bubble mass after bubble formation, because the initial bubble mass is known.

The injection and withdrawal rates (1/sec) are given by the following relationships for the assumed cycle

$$\dot{m}_{withdrawal}(1/sec) = \frac{1}{3600}\frac{\lambda}{50\,\psi}\,M_{bubble,initial}$$

$$\dot{m}_{injection}(1/sec) = (1-\psi)\frac{1}{3600}\frac{\lambda}{40\,\psi}\,M_{bubble,initial}$$

where λ is the cycling fraction (0.1) and ψ is the fraction of mass (0.4) injected on the weekend (including Friday evening). There are a total of 50 hours of withdrawal and 40 hours of injection during the week. Air is injected for 26 hours and 40 minutes over the weekend; 10 hours Friday and 16 hours 40 minutes Sunday.

The injected air is assumed to be dry and at 25°C, the same temperature as the reservoir. These assumed conditions necessitate the use of compressors with intercoolers and an aftercooler to compress, cool, and dehumidify the air being injected into the reservoir (Succar and Williams, 2008).

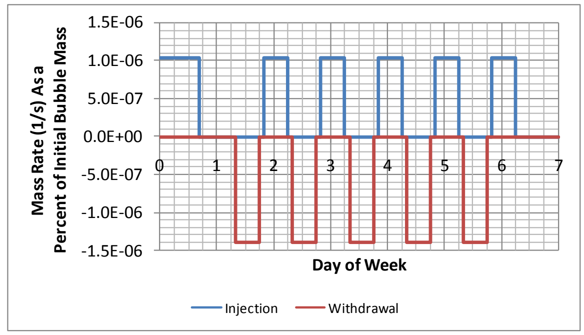

Figure 3. Injection and withdrawal mass flow rates

Two-phase Characteristic Curves

The formation is assumed to be sandstone with isotropic properties. Two-phase characteristic curves (van Genuchten (1980) and Corey (1954)) are based on the work of Zhou et al. (2010). The capillary pressure is scaled using the Leverett J-function (Leverett, 1941).

Borehole Model

The borehole is modeled as a porous medium with a porosity of 1.0 and a permeability of 10^{-7} m^2. Zero capillary pressure was specified. Due to the flow of liquid into and out of the borehole during CAES cycling, linear relative permeability was specified for the liquid and gas phases. The relative permeability for each phase increased over the range 0.01 to 1.0, although the lower limit was sometimes varied to promote convergence. The borehole volume is that of the actual borehole all the way to the surface.

Mesh

The simulations use an R-Z axisymmetric mesh assuming zero dip. The first radial mesh point is the borehole radius, which for the 7-inch diameter borehole is 0.292 ft (0.0889 m). The maximum radial dimension is 1000 ft (305.1 m) with logarithmic mesh spacing between these two points and 44 radial increments. The axial mesh spacing is a uniform 10 ft (3.048 m). The maximum axial value is 100 ft (30.48 m), which is the top of the formation. The minimum axial value is -20 ft (6.096 m). The part of the mesh below the bottom of the formation is a constant head boundary condition to maintain hydrostatic conditions in the formation. Air may not flow into the bottom 20 ft of the mesh while water may flow out to maintain hydrostatic pressure.

RESULTS

Simulation Procedure

The formation is assumed to be initially water saturated at hydrostatic conditions. An air bubble is formed in the formation by injecting air into the formation for 60 days at a constant rate based on the desired initial air bubble mass, which is a function of the formation radius and porosity (pore volume) and the desired final formation gas saturation value. The formation then "rests" for 40 days (no injection or withdrawal to simulate an equilibration period) before CAES injection and withdrawal begins. CAES injection and withdrawal is based on the initial air bubble mass and continues for 70 days (10 weekly cycles). The minimum and maximum pressure at the borehole/formation interface for the last CAES weekly cycle are evaluated and compared to the minimum and maximum limits. The formation radius is iteratively adjusted until either the desired minimum or maximum pressure is reached.

Example Simulation Results

Base-case results are shown in Figure 4 for a borehole diameter of 7 inches (17.8 cm) with a formation permeability of 500 mD, a porosity of 0.2, and a formation radius of 378 ft (115.3 m). Figure 4a shows the pressure variation of the formation with time as the gas bubble forms, which occurs for the first 60 days with a desired 50% gas saturation, followed by 40 days of zero injection. The initial bubble mass is 2.06×10^7 lbm (9.33×10^6 kg). Based on this initial bubble mass and the CAES cycle, the mass rate is 21.5 lbm/s (9.72 kg/s) during injection and 28.6 lbm/s (12.96 kg/s) during withdrawal. The pressure during cycling is shown in Figure 4b. Time zero occurs when the cycling starts at 100 days; cycling continues for 10 weeks. The minimum and maximum pressures during the last cycle are 708 psia (4.88 MPa) and 1043 psia (7.19 MPa). The formation pressure reaches consistent values from cycle to cycle after about five weekly cycles.

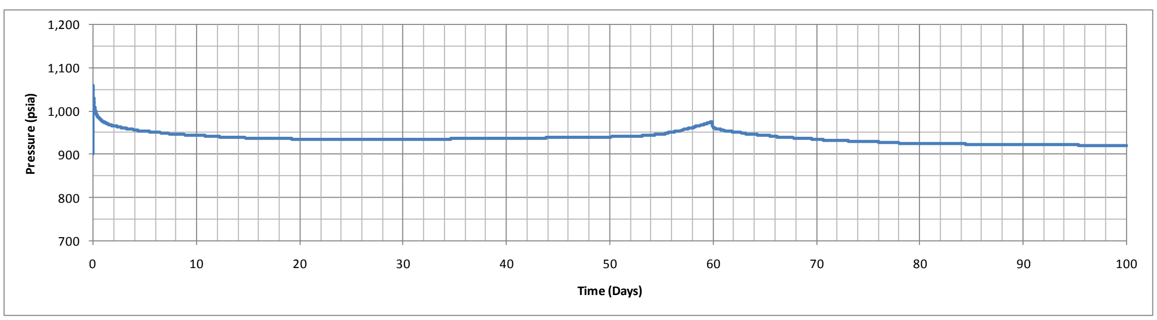

Figure 4a. Formation pressure during air bubble development and rest period

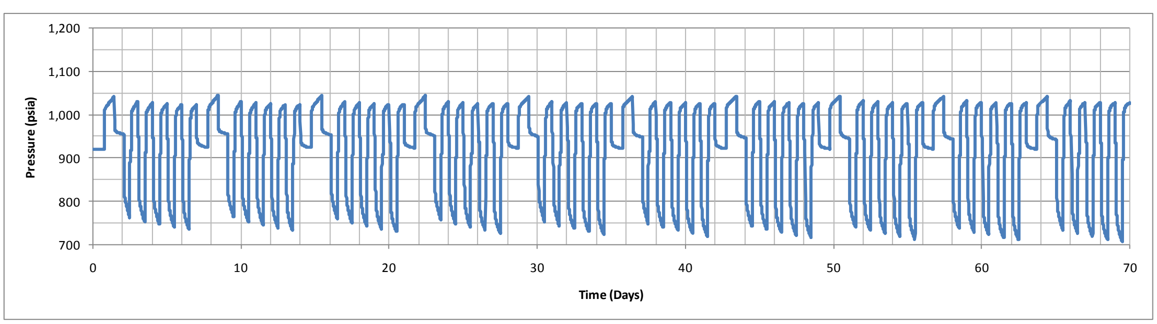

Figure 4a. Formation pressure during air cycling

Formation Radius Results

The base-case simulation results given above are for a given formation radius. The calculated response depends on the formation radius, which is varied by discrete values using the original mesh. Varying the formation radius changes the initial air bubble mass, which, in turn, changes the mass injection and withdrawal rates, which then affect the minimum and maximum pressure at the borehole/formation interface.

Figure 5 shows the CAES borehole withdrawal rate as a function of formation radius for a borehole diameter of 7 inches (17.8 cm), a formation permeability of 500 mD, and a porosity of 0.2. As the formation radius increases, initial air bubble mass/volume increases, as does the injection and withdrawal rate. Figure 6 plots the maximum and minimum borehole/formation pressure at formation depth for different formation radii. The dashed lines are maximum and minimum pressure limits.

The formation radius where the calculated pressure (either minimum or maximum) first crosses a limit is the optimal formation radius for a specific set of formation parameters and depth. The optimal radius is obviously a function of the air-bubble formation parameters, such as the desired gas saturation and the CAES weekly cycle details.

For the base-case formation parameters, the optimum formation radius is about 365 ft (111 m), or slightly less than the value used in the example simulation given above. As can be seen by those results, the minimum pressure shown in Figure 4 (bottom) is slightly below the minimum pressure of 725 psia (5.0 MPa). Consequently, the optimal radius, as well as the corresponding mass injection and withdrawal rates, will be slightly lower than those given in the example.

Note that the mass withdrawal rate influences the minimum pressure, while the mass injection rate results in the maximum pressure. In this case, the pressure limit is due to the mass withdrawal rate.

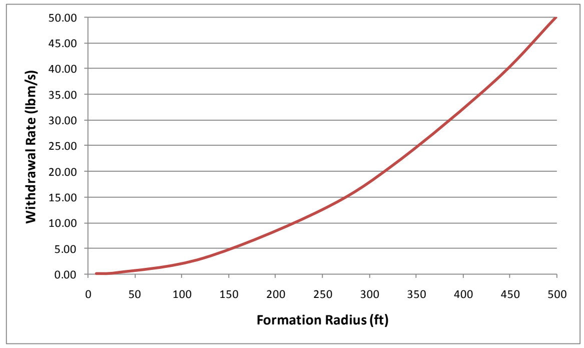

Figure 5. Borehole withdrawal rate vs. formation radius.

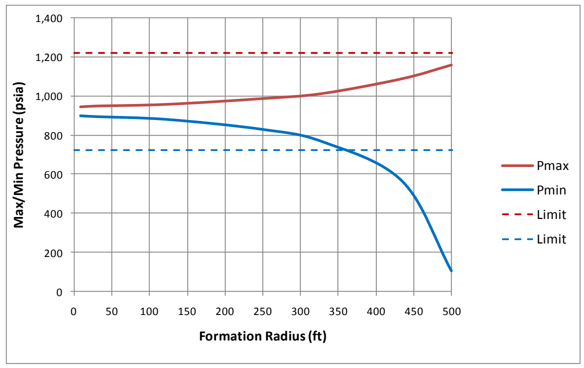

Figure 6. Max/min pressure vs. formation radius.

The results presented above used a permeability of 500 mD and a porosity of 0.2. Sensitivity studies were performed to assess how varying these parameters affected the viability of different formations. The permeability was varied between 100 mD and 2000 mD, while the porosity range was from 0.1 to 0.3. The borehole diameter was also varied from 7 inches to 20 inches. The pressure limit reached in the majority of the cases is the minimum pressure.

Figure 7 summarizes the results. The effect of the borehole diameter is minimal because of the low frictional pressure drop in the borehole. The effect of permeability is larger than porosity. An increase in permeability increases the borehole spacing, while an increase in porosity decreases the borehole spacing.

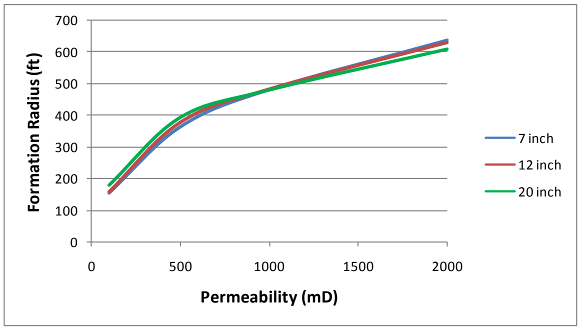

Figure 7a. Effect of permeability and borehole diameter on the formation radius

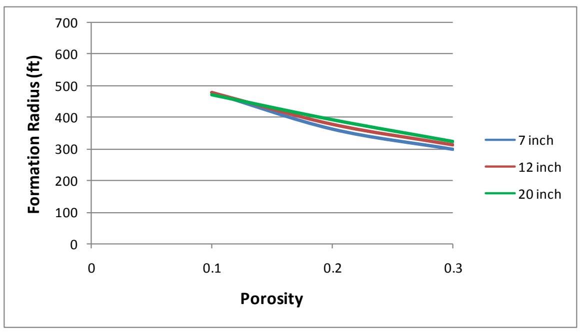

Figure 7b. Effect of porosity and borehole diameter on the formation radius

The formation radius increases with permeability because more of the formation is accessible to the air for a given pressure difference. For porosity, an increase in porosity reduces the formation radius but increases the accessible volume for the air, even for a reduced formation radius.

The results can be further extrapolated to examine MW per borehole and the footprint for a given power plant. Based on Succar and Williams (2008), the power per borehole is approximately 0.335 MW/lbm/s (0.74 MW/kg/s). The approximate MW per borehole is shown in Figures 8a and 8b as a function of permeability and porosity.

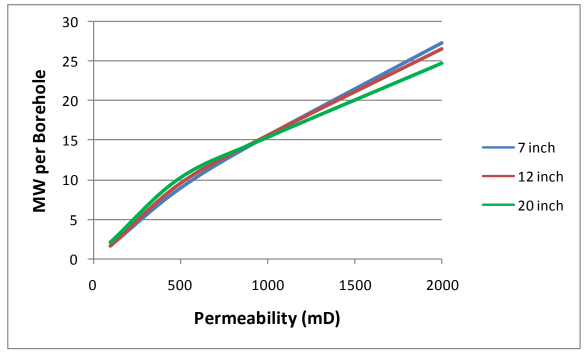

Figure 8a. Effect of permeability and borehole diameter on the MW per borehole

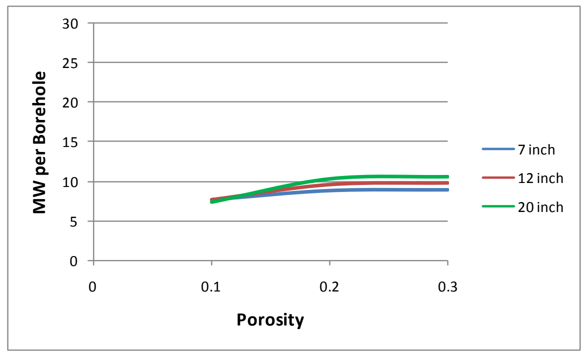

Figure 8b. Effect of permeability and borehole diameter on the MW per borehole

ADDITIONAL STUDIES

The above results are summarized in Webb (2011). Pan et al. (2009, 2011a,b) developed an open borehole model for CO_2 applications. More recently, Pan (2012) extended the open borehole model to the water-air equation of state. Additional studies have been conducted for the present problem using this new model. The current results with the porous medium borehole model assumed a 75 psi (0.5 MPa) pressure drop from the formation to the surface. Using the Pan et al. (2012) borehole model, the pressure drop from the formation to the surface for the base case varied between 45 and 80 psi (0.31–0.55 MPa) with an average value of about 60 psi (0.41 MPa), supporting the previous pressure drop assumption.

Additional studies have also been performed for the simulation model boundary condition. The current results assumed that the bottom of the formation sets the hydrostatic pressure of the formation. In more recent studies, the bottom boundary has been made impermeable, and the outer radius boundary condition establishes hydrostatic conditions for the formation. In this revised case, the formation pressure during air-bubble formation is significantly higher by about 180 psi (1.2 MPa) than the original boundary condition. However, the maximum and minimum cycling pressures are essentially the same as they cycle around the local hydrostatic pressure. Neither set of boundary conditions is correct, but one has to impose hydrostatic conditions somewhere to constrain the results.

SUMMARY AND CONCLUSIONS

A 2-D borehole/formation model was developed for CAES applications to evaluate the performance of the system under various conditions, including two-phase flow. Based on minimum and maximum formation pressure values, the optimal formation radius, which is directly related to borehole spacing, was determined for given sets of formation parameters, borehole diameters, and CAES operating assumptions.

For the conditions addressed in this report, the borehole diameter had a minor influence on all the parameters including the borehole spacing and the power per borehole. These differences are not considered significant due to the uncertainties in the model.

The effect of two formation parameters, permeability and porosity, on the operational parameters was assessed using this model. Changes in formation permeability had a much more dramatic effect than changes in porosity.

These results should help guide the selection of formations for CAES applications by evaluating the influence of different formation parameters. The information on borehole diameter and spacing, and the dependence on formation parameters, can be used to help assess the feasibility of a CAES facility in a reservoir.

ACKNOWLEDGMENT

This work was sponsored by the DOE Energy Storage Systems Program under contract to Sandia National Laboratories. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

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